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Introduction

All solar activity including sunspots, solar flares, prominence eruptions and coronal mass ejections is a product of the Sun's magnetic fields. The interaction between plasma flows and the magnetic field within the Sun's convection zone (the outermost 30% of the solar interior) produces the magnetic flux. This flux erupts through the Sun's photosphere in active regions (sunspots) which appear in low latitude bands on either side of the Sun's equator. As the active regions decay, the magnetic flux is transported across the Sun's surface by flows in near the surface layers. An important consequence from this transport is the reversal and production of the Sun's polar fields during each 11-year solar cycle (evident in Figure 1). These polar fields are reliable predictors of the strength of the following solar cycle.

Hathaway and Rightmire (*Science* 327, 1350 2010) measured the axisymmetric transport of magnetic flux over the course of Solar Cycle 23 (1996-2008) and initial rise of Solar Cycle 24 (2009-2010) using line-of-sight magnetograms from the Michelson Doppler Imager (MDI) instrument on the ESA/NASA Solar and Heliospheric Observatory (SOHO) Mission. Significant and systematic variations in the strength and structure of the poleward Meridional flow were clearly observed over the 14 year period. A key aspect to these variations is their effect on the polar magnetic fields.

The variations in the polar fields can be attributed to variations in the Meridional Flow at high latitudes. Meridional Flow remaining strongly poleward in the polar regions produces stronger polar fields while the weaker polar fields are produced by weaker flows and/or counter-cells in the polar regions. This project addressed this problem by measuring the Meridional Flow to higher latitudes and with better precision using data from Helioseismic and Magnetic Imager (HMI) on board the NASA Solar Dynamics Observatory (SDO) satellite.

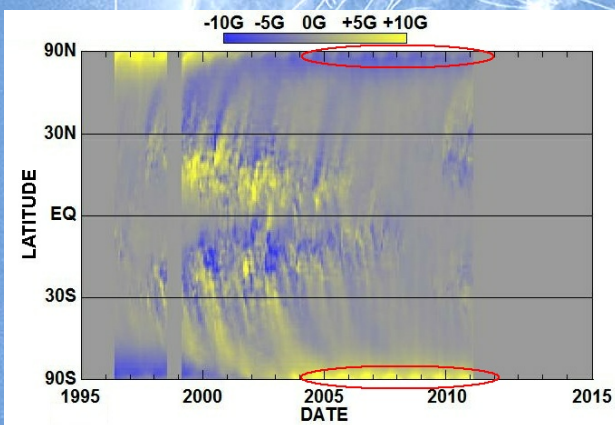


Figure 1: A magnetic butterfly diagram constructed using data assimilated from SOHO/MDI with symmetric north-south transport. Note the annual signal near the poles marked by the red ovals – the field is weak in the Spring and strong in the Fall.

Abstract

We measured the flows of magnetic elements on the Sun at very high latitudes by analyzing magnetic images from the Helioseismic and Magnetic Imager (HMI) on the NASA Solar Dynamics Observatory (SDO) Mission. Magnetic maps constructed using a fixed, and north-south symmetric, meridional flow profile give weaker than observed polar fields in the North and stronger than observed polar fields in the South during the decline of Cycle 23 and rise of Cycle 24. Our measurements of the meridional flow at high latitudes indicate systematic north-south differences. There was a strong flow in the North while the flow in the South was weaker. With these results, we have a possible solution to the polar field asymmetry. The weaker flow in the South should keep the polar fields from becoming too strong while the stronger flow in the North should strengthen the field there. In order to gain a better understanding of the Solar Cycle and magnetic flux transport on the Sun, we need further observations and analyses of the Sun's polar regions in general and the polar meridional flow in particular.

Procedure

We downloaded 720-second averaged Full Disk Magnetograms from the HMI instrument centered at the top of each hour. The data were mapped into heliographic coordinates. We then measured both the differential rotation and the meridional flow by cross-correlating data strips from pairs of these magnetic maps separated by 8 hours as shown in Figure 2. Here we concentrated on measurements of the meridional flow during the one year of the MDI-HMI overlap — Carrington Rotations 2096-2107. Measurements were attempted at latitudes up to 85° in both the North and South but were limited to latitudes less than ~75° when the tilt of the Sun's rotation axis was unfavorable. Typically, measurements were obtained from about 600 image pairs during each 27-day rotation of the Sun.

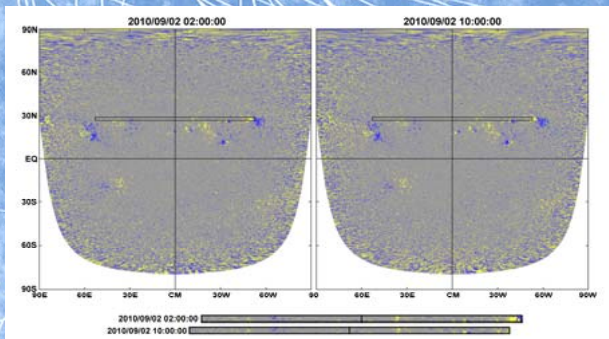


Figure 2: Two magnetic maps constructed from data obtained 8 hours apart. Strips of data from each map are cross-correlated to determine how far the magnetic pattern shifts in longitude and latitude.

Results

We find that we can use HMI to reliably measure the meridional flow to within 5° of the poles (red lines in Figure 3). Our HMI measurements agree with those obtained with SOHO/MDI data (black lines in Figure 3) at latitude below ~20°. In the mid latitudes, ~20-60°, HMI results are slight slower than was found with MDI. Furthermore, HMI measurements show a poleward MF all the way to the poles. This is contrary to the previous MDI measurements suggesting a counter-cell in the North and flow to the pole in the South. We do find a slight, but potentially important, North-South asymmetry in the HMI Meridional Flow – the poleward flow is faster in the North and slower in the South. These results provide us with a possible explanation for the annual signal near the poles on the magnetic butterfly diagram (Figure 1).

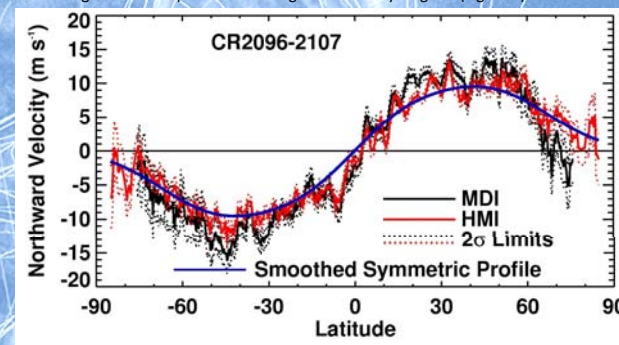


Figure 3: The Meridional Flow from Carrington Rotations 2096-2107. Results from HMI are shown in red and results from MDI are shown in black. The HMI smoothed symmetric profile is shown in blue.

Conclusions

We have measured the meridional motions of magnetic elements on the Sun by cross-correlating data from magnetic maps derived from SDO/HMI 720-second magnetograms. The measurements are more accurate and extend to higher latitudes than those previously obtained. We find North-South asymmetries in the Meridional Flow that may help explain the asymmetries seen in the Sun's polar magnetic fields. Calculations using North-South symmetric Meridional Flow produce weaker than observed polar fields in the North and stronger than observed polar fields in the South (the annual signal seen in Figure 1). The stronger meridional flow we observe in the North should strengthen the calculated polar fields there while the weaker meridional flow in the South should weaken the calculated polar fields at the South Pole. These conclusions can be confirmed by calculations of the Sun's magnetic flux transport using these newly observed flow profiles.

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